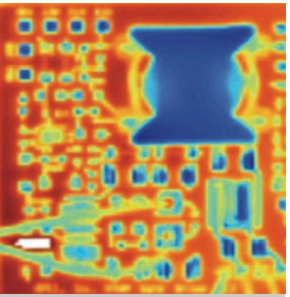

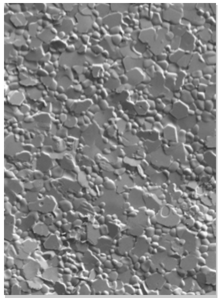

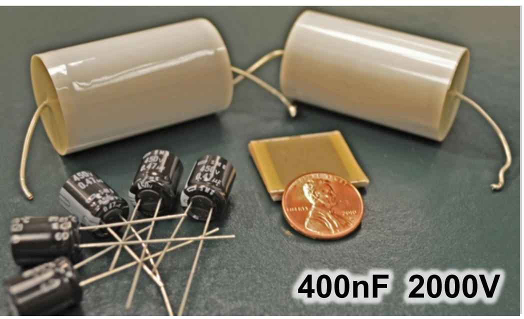

High Temperature Capacitor Development for Reliable Operation in Inverter Applications

18 Sept 2014

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Sandia National Laboratories

**Now at Colorado School of Mines*

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NNSA National Nuclear Security Administration

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    - John Borchardt
    - Alice Kilgo and Bonnie McKenzie
    - Adrian Casias and Adrian Wagner
    - Clayton Cozzan and Kelsey Meyer (summer students)
    - Stan Atcitty
  - Honeywell: Kansas City Plant

Project Overview

This project is motivated primarily by cost reduction

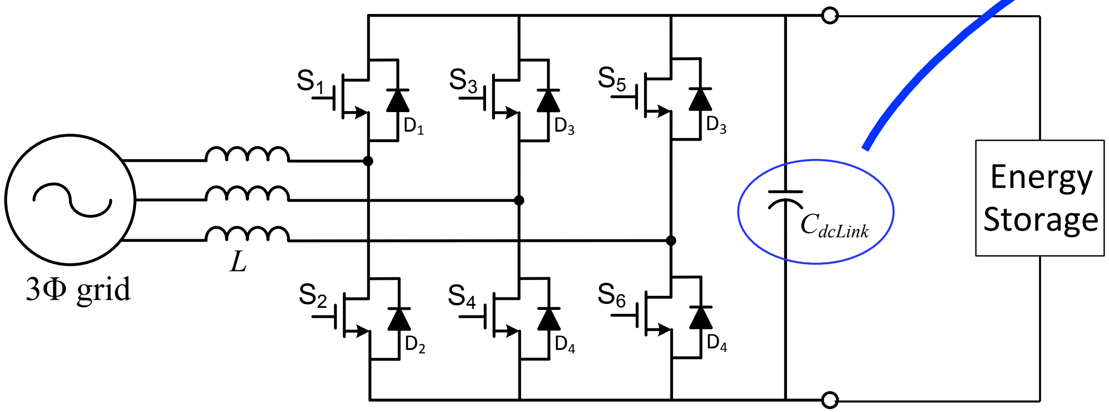
Performance → Reliability → Cost

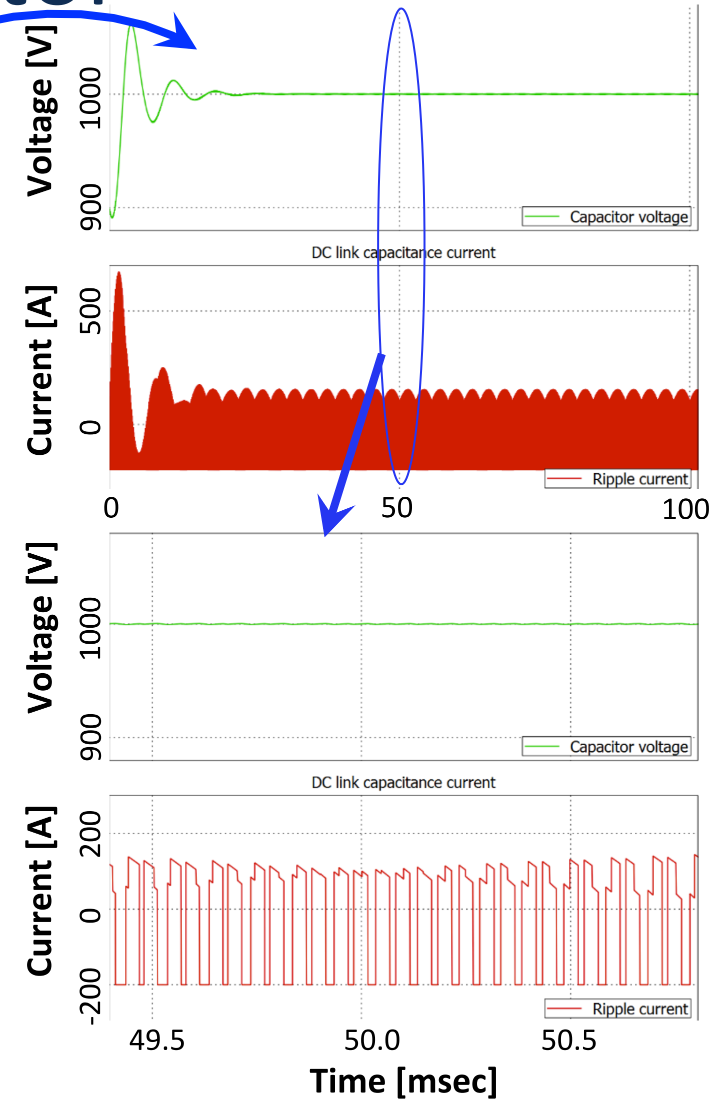
Impact on system

- Capacitors represent one of the top two sources of failure and volume in power electronics modules
- Advances in WBG semiconductor devices mean that operating temperature limitations are imposed by capacitors and packaging
  - Higher power
  - Greater efficiency
- Power electronics systems with reduced thermal management requirements are highly desirable for stationary and transportable storage
  - High power density
  - Reduced complexity
  - Reduced cooling-related failures
- Available high operating temperature capacitors fail to meet the criteria for desired performance and reliability
  - Severe derating
  - Large volume
  - Expensive

***GOAL*-Produce reliable high temperature capacitors**

Improved DC Link Capacitor



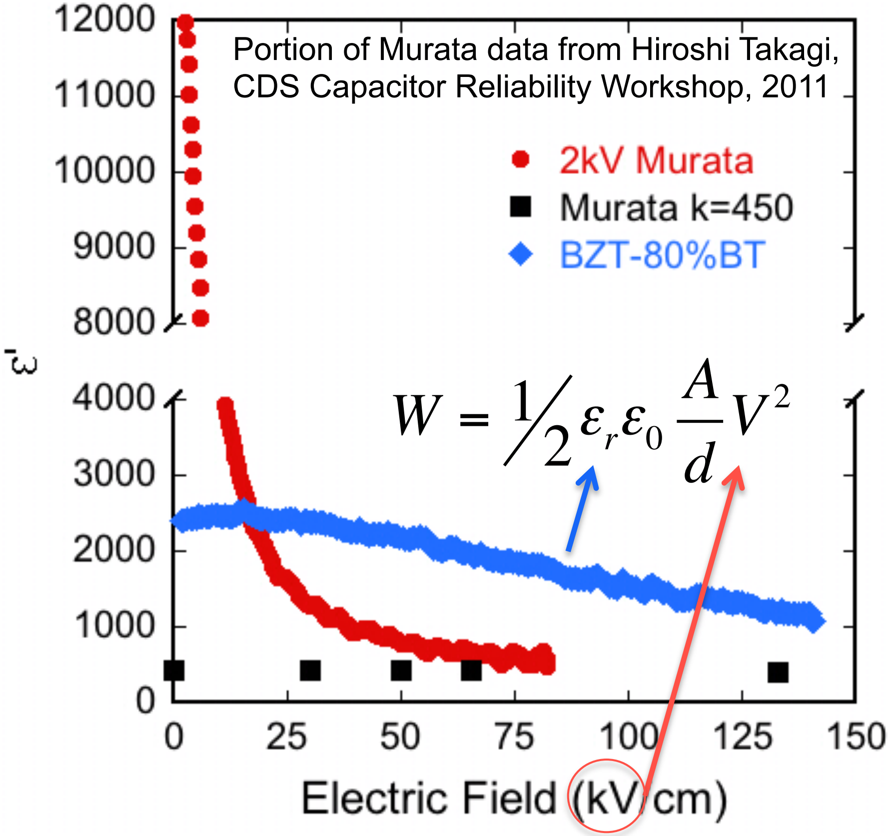


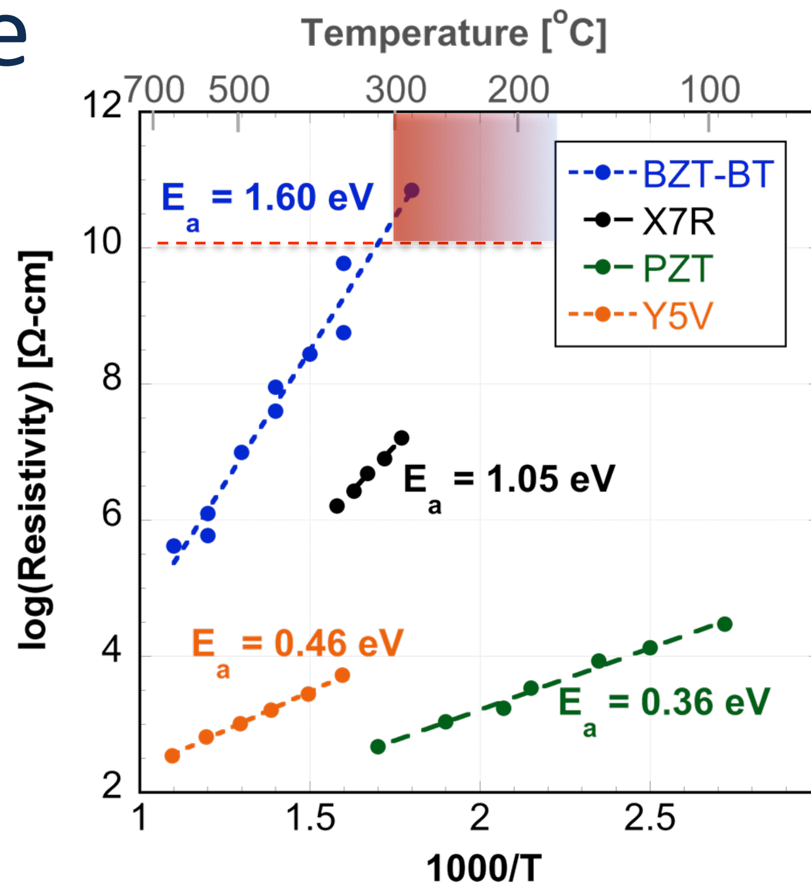
- Uncooled operation above 200-300°C ambient
- 1-5kV, 100s of A at >20kHz with >30 year lifetime
- Microfarad to millifarad capacitance values needed
- **Compact & Inexpensive**
- ***Low ESR and ESL is critical for high frequency response, ripple current and power handling***

Capacitors account for up to half of the volume, nearly half of the cost, and are responsible for at least half of the failures in today's inverters.

Switching transient simulation courtesy of Stan Atcitty

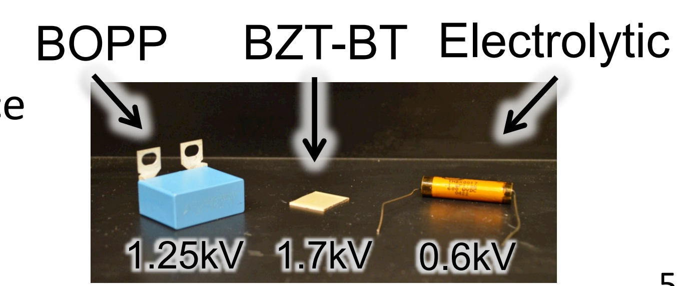
Goal: Stable Capacitance and Insulation Resistance



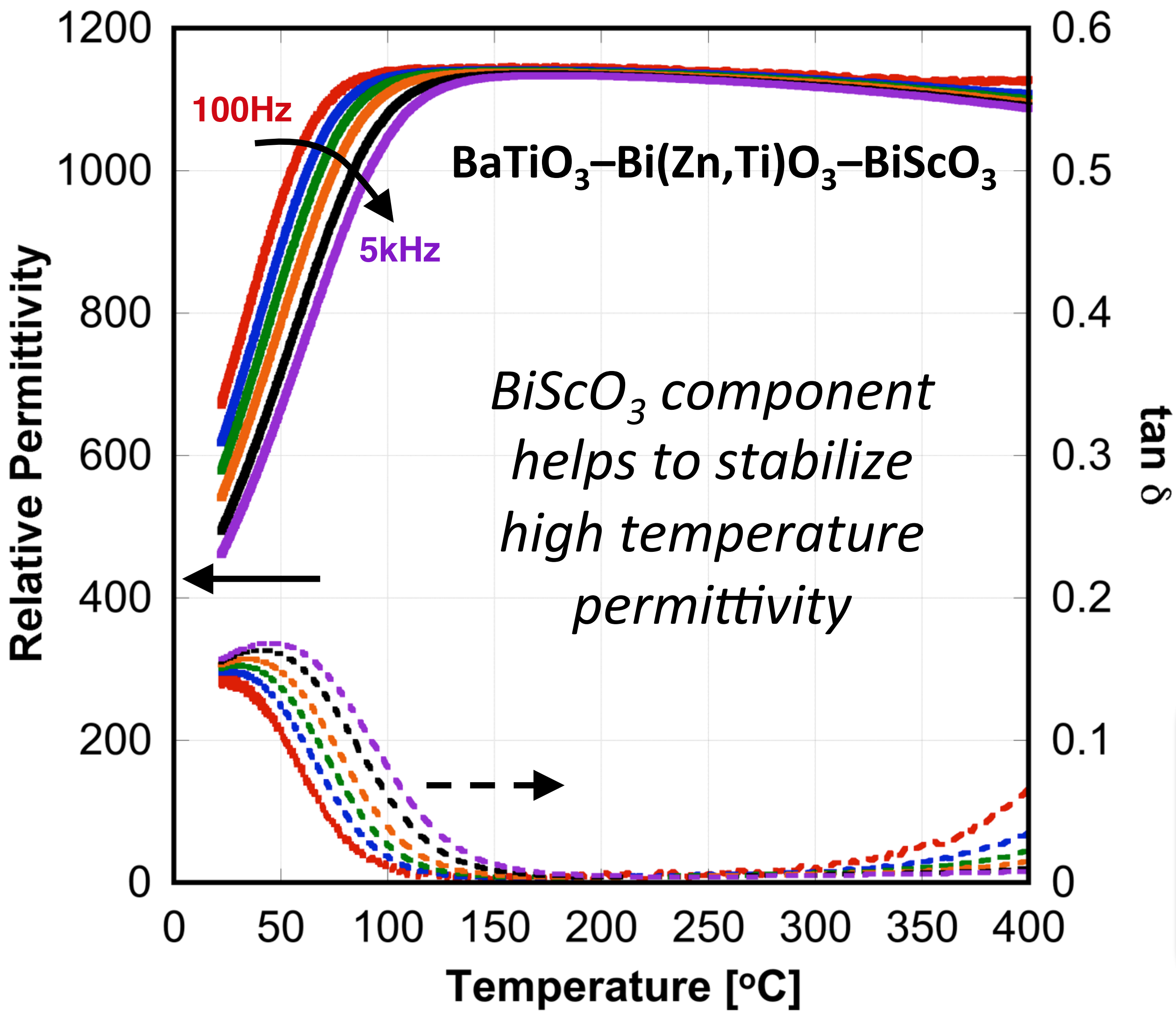


In prior years, this project developed and demonstrated:

- Novel dielectrics with outstanding electrical performance
- Multilayer capacitors based on these dielectrics that offered significant size and operating temperature advantages



High Temperature Operation



with Prof. David Cann, Oregon State University

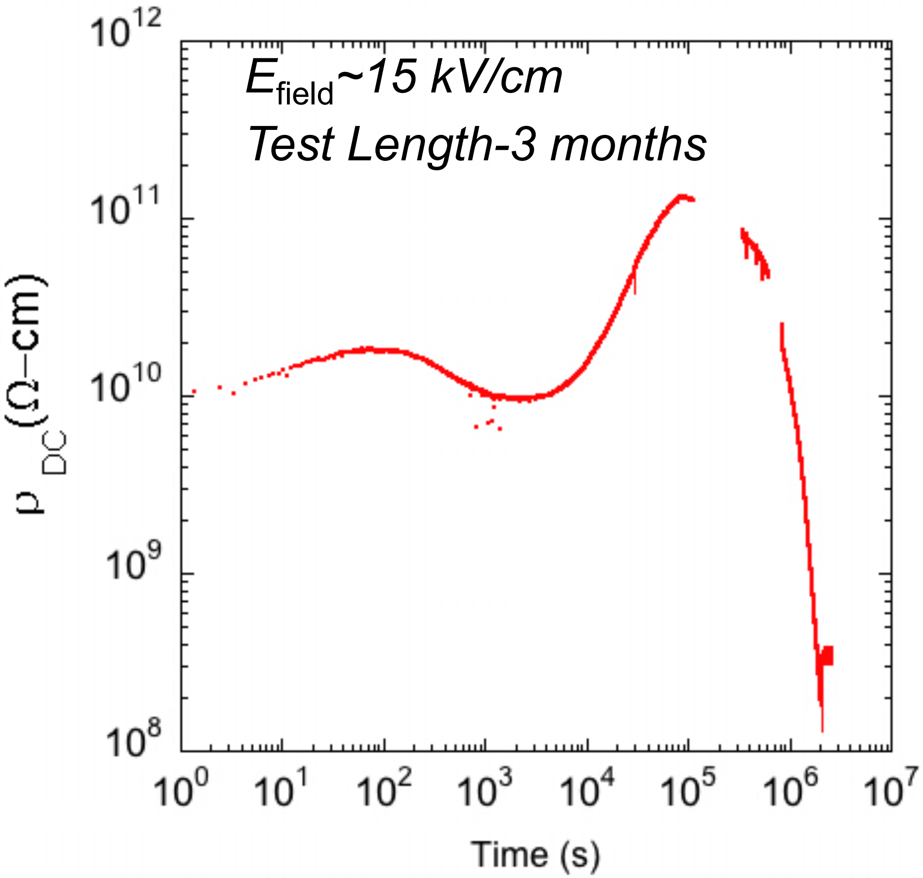
Sc_2O_3 > $7,000/kg (per atom, roughly equivalent to Pt)

Global annual production of Sc_2O_3 <10,000 kg

Current MLCC production is over 100,000 kg/yr

For large-scale viability, it is important to develop materials with similar performance that do not require significant amounts of Sc_2O_3

Understanding long-term reliability

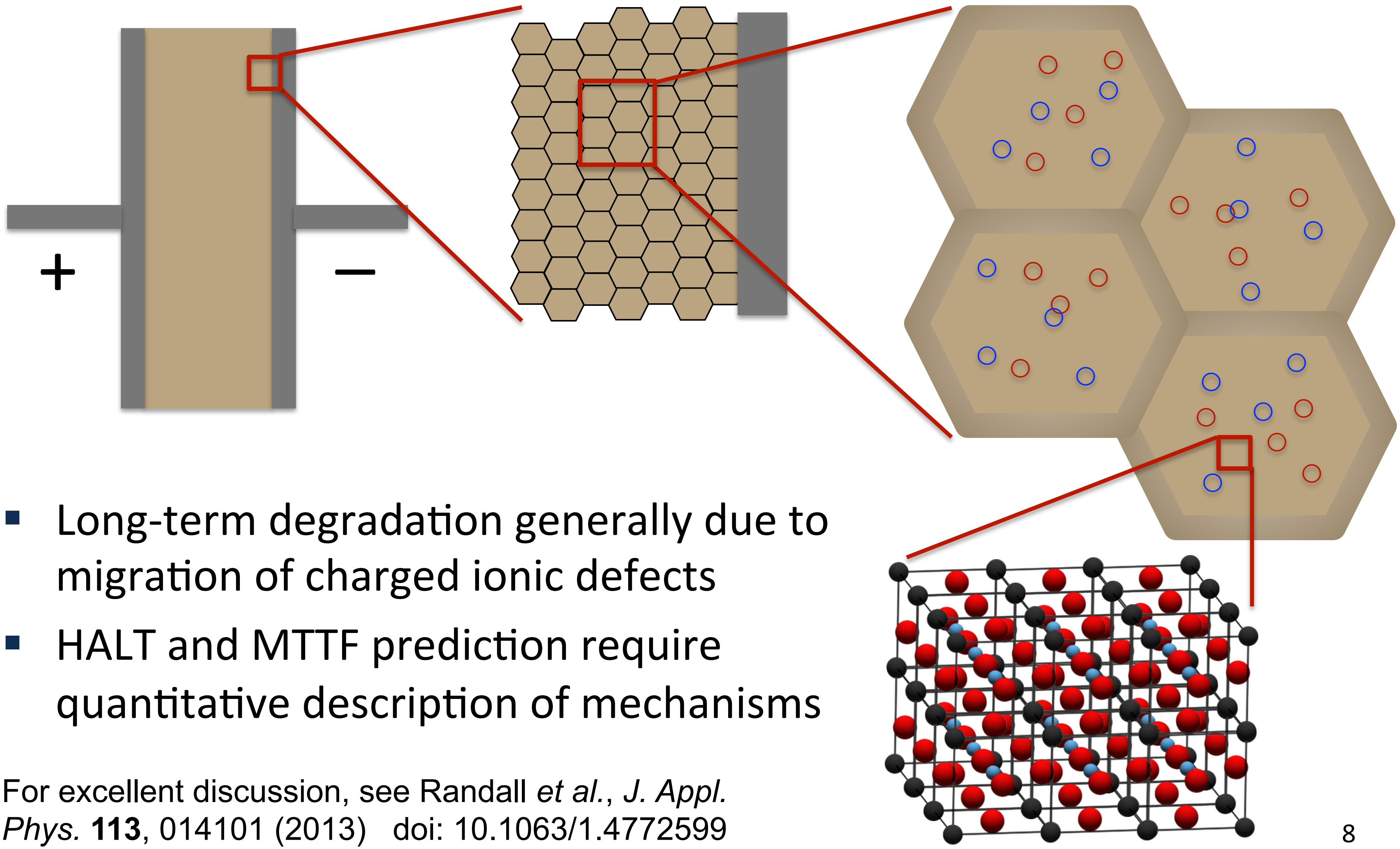


- Dielectric stress in disc capacitor held constant at at 250°C
- Multiple aging mechanisms were observed in the parent dielectric $0.2BiZn_{1/2}Ti_{1/2}O_3$-$0.8BaTiO_3$

Reduction in DC resistivity during operation results in joule heating and eventual thermal failure of dielectric

Understanding the dominant aging mechanisms in capacitors at high temperature is necessary to extend the life of power electronics modules

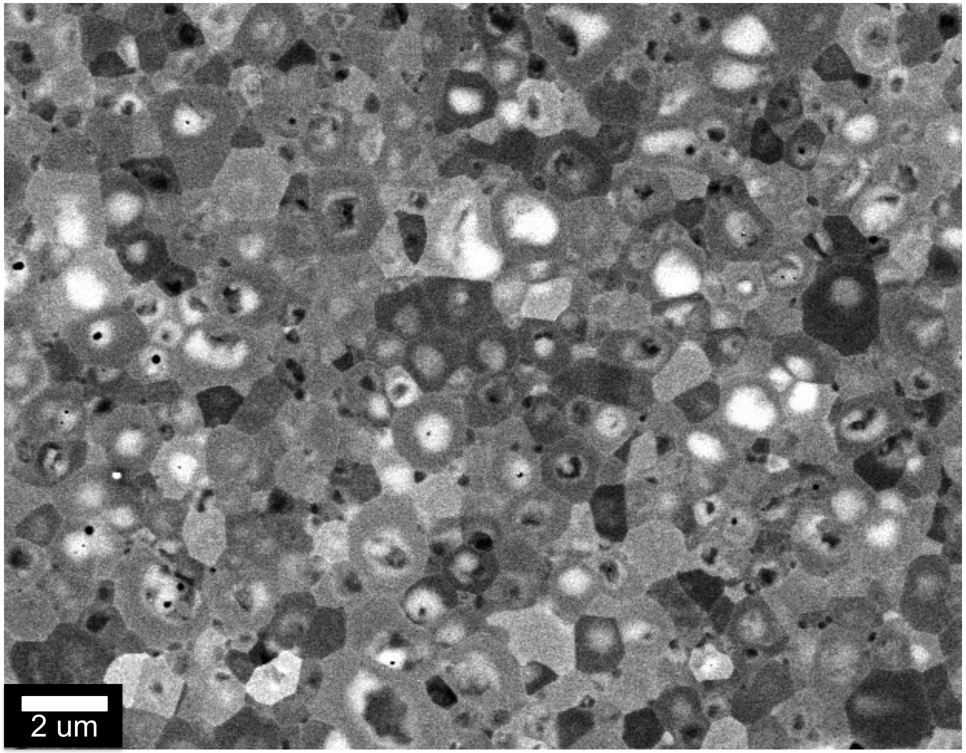
Degradation in Ceramic Dielectrics



- Long-term degradation generally due to migration of charged ionic defects
- HALT and MTTF prediction require quantitative description of mechanisms

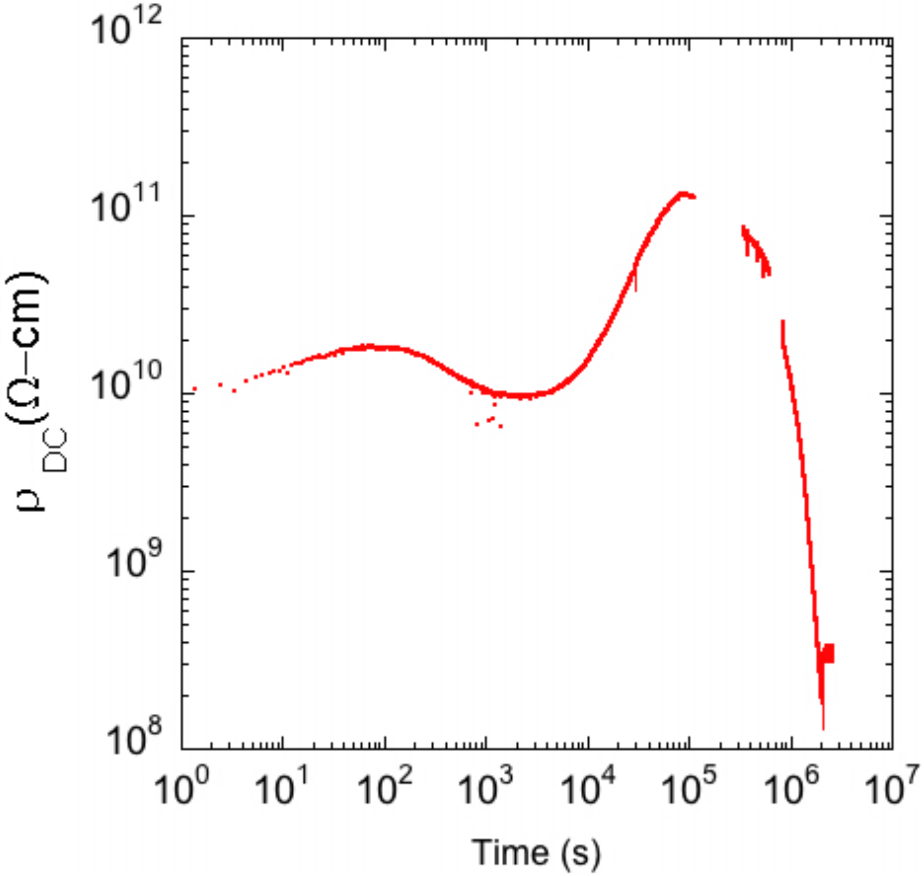
For excellent discussion, see Randall *et al.*, *J. Appl. Phys.* **113**, 014101 (2013) doi: 10.1063/1.4772599

Understanding long-term reliability



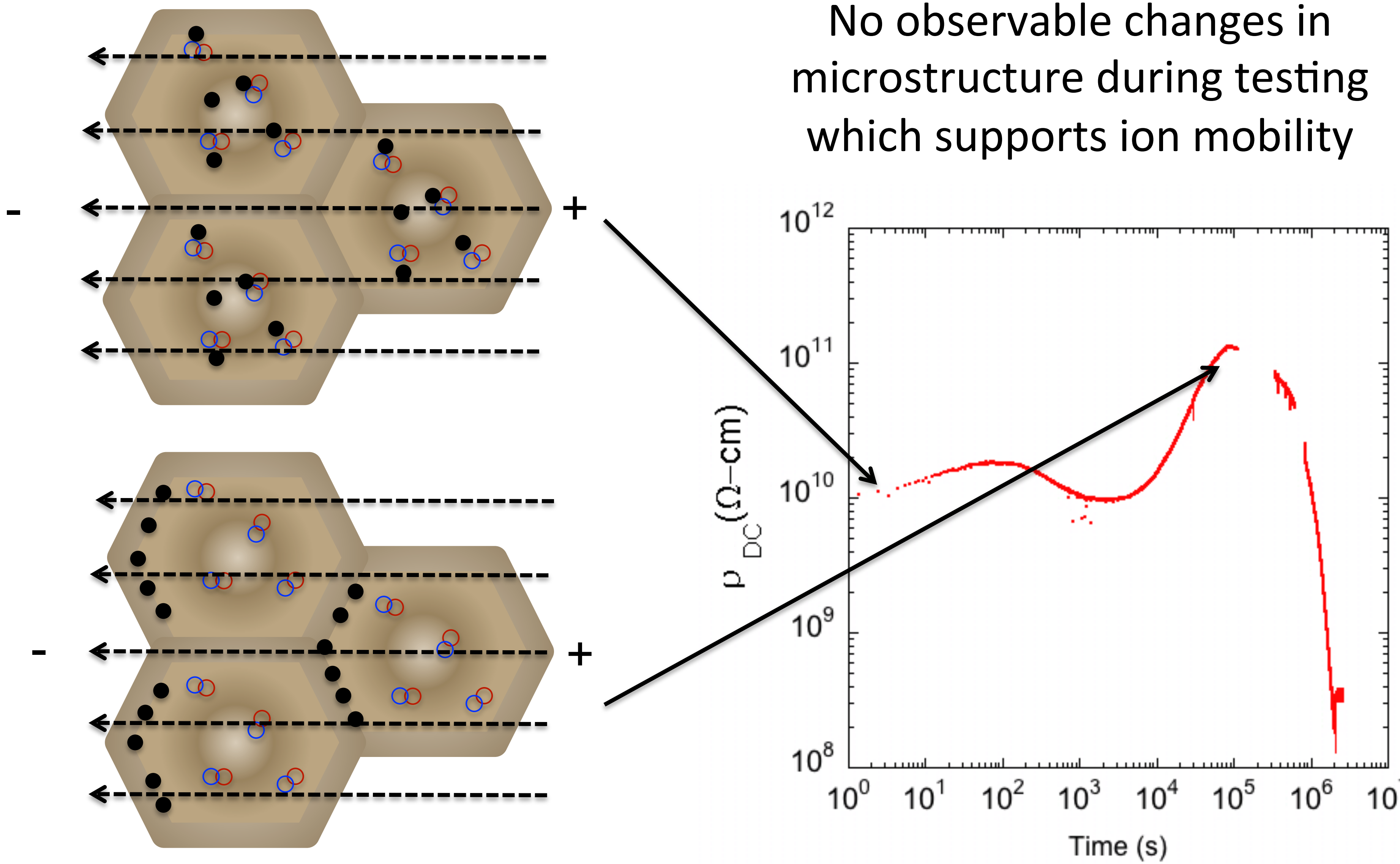
How does the inherent microstructural non-uniformities improve the performance during aging?

Dielectric stress in disc capacitor held constant at 250°C

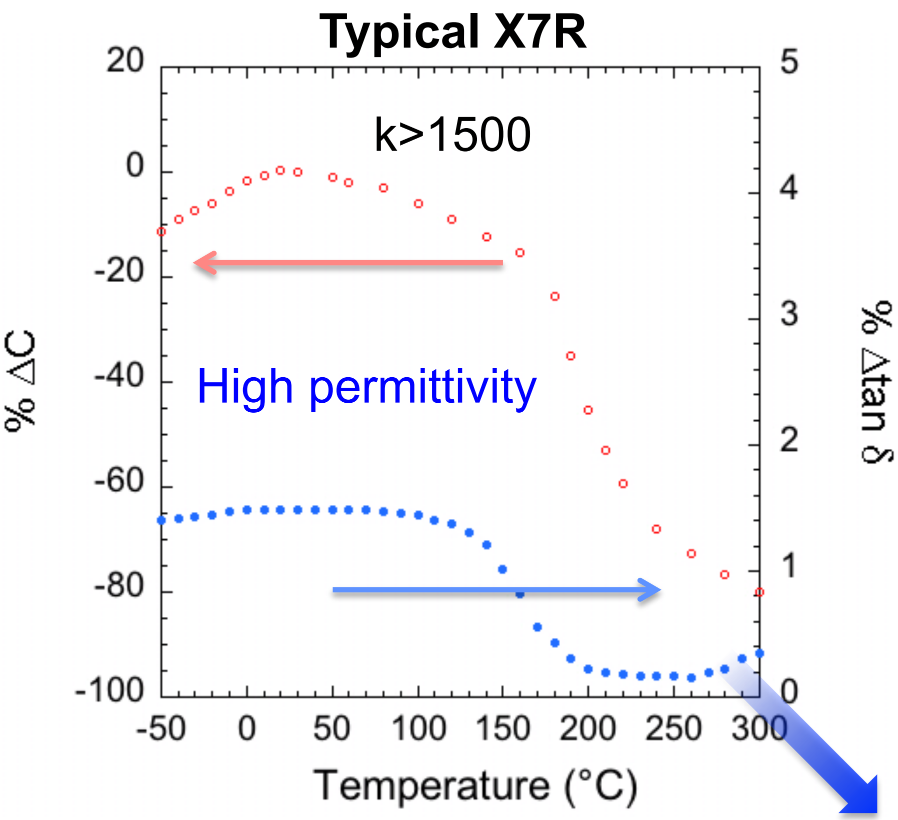


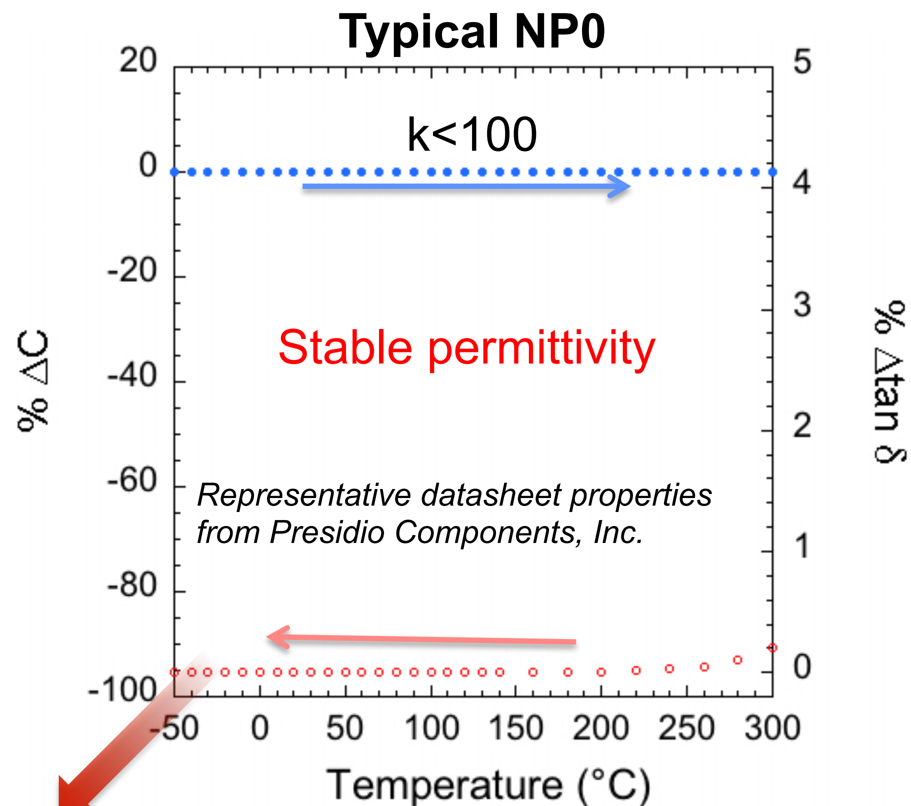
Understanding long-term reliability

No observable changes in microstructure during testing which supports ion mobility



Industrial technology transfer





Present NP0 capacitors do not meet the reliability requirements for grid scale power electronics:

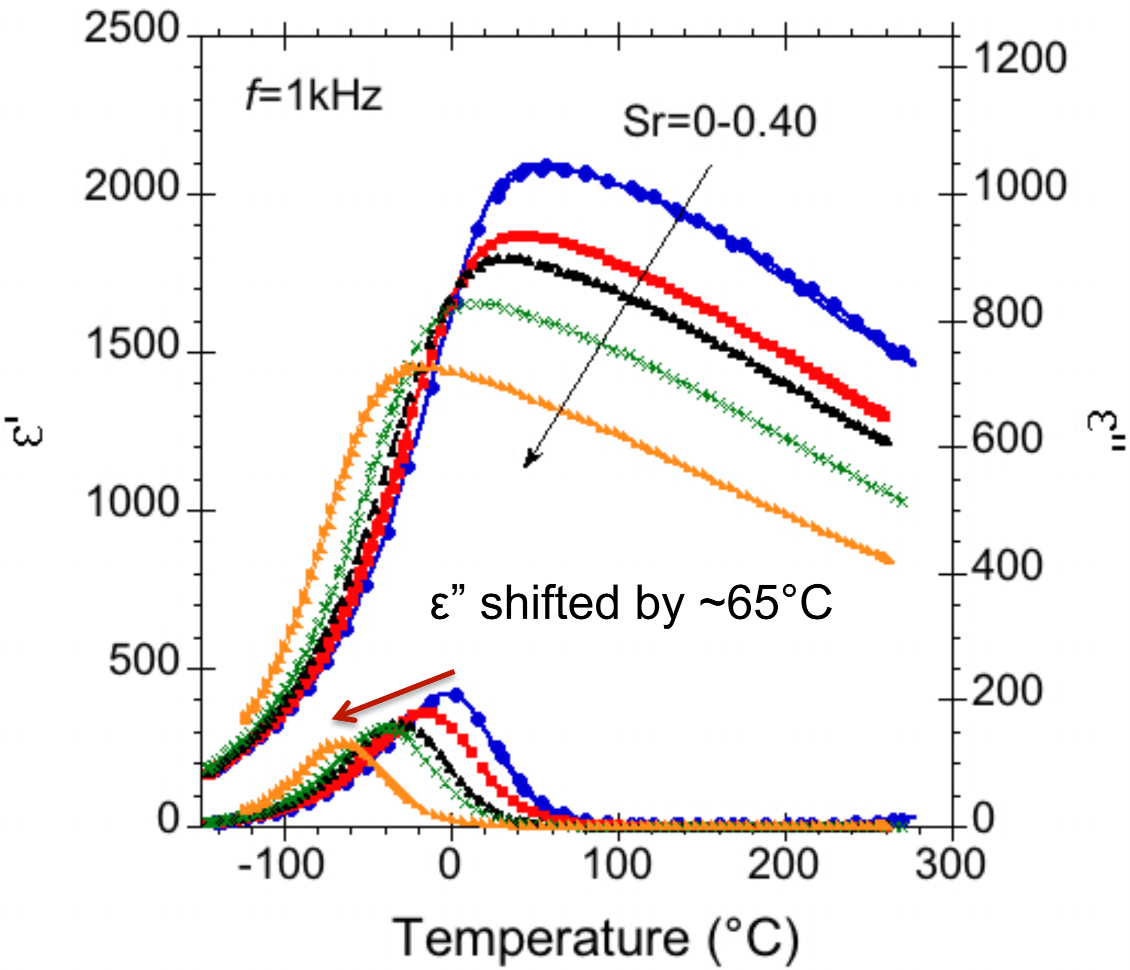
Gap in product space

New Dielectrics

>30 Year Reliability

SNL is working with leading dielectric manufacturers in New York and California to transition this technology to the private sector

Chemistry controls operating range

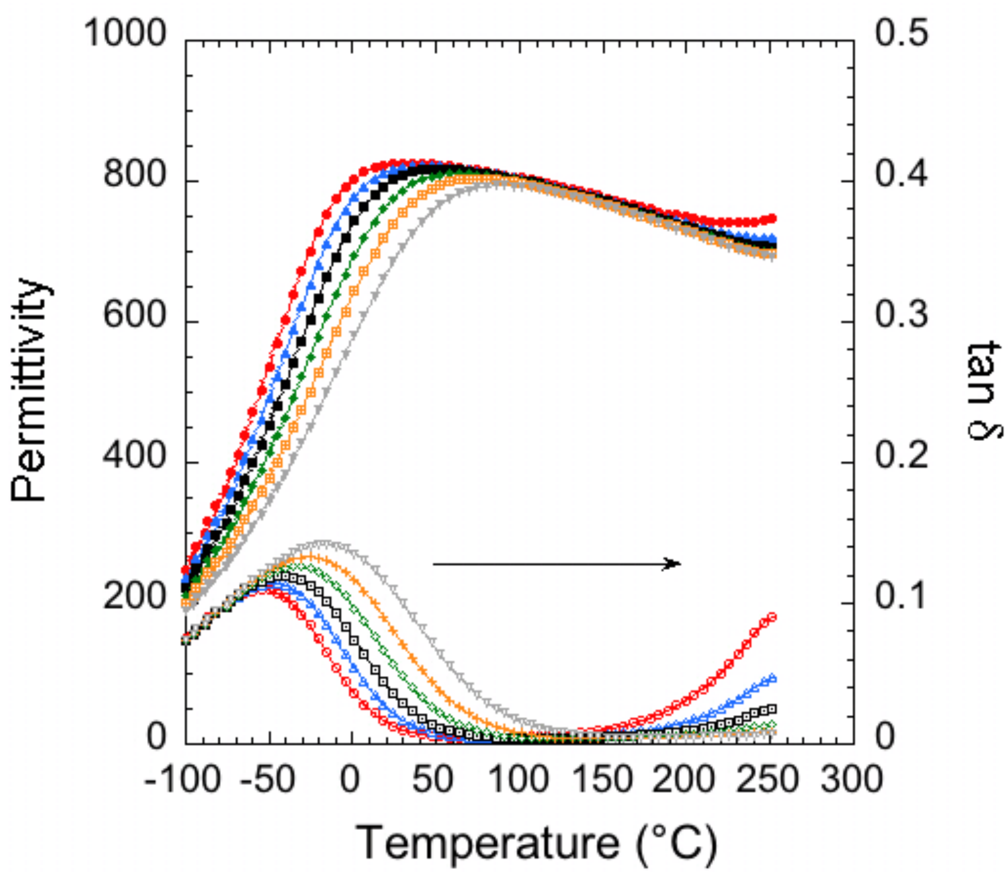


Sr (%)	TCε' (ppm/K)
0	-1338
5	-1464
10	-1479
20	-1474
40	-1603

$$TC\varepsilon' = \frac{-(\varepsilon'_{max} - \varepsilon'_{max@+180^\circ C})}{\varepsilon'_{max@+90^\circ C}(180^\circ C)}$$

- Dielectric relaxation should be below 0°C for high frequency
- What can we do to mimic the performance of $BiScO_3$ systems with lower cost?

Reducing the dielectric cost



Commercial partners have asked for the Al-substituted composition for scale up

Dielectric Cost Reductions

Low cost Sc-dopant substitutions: Al, Y, Fe, and Ga

Metallization Cost Reductions

High permittivity compositions reduce the number of precious metal layers required to achieve high capacitance

System Cost Reductions

High reliability reduces costs linked to maintenance, system failure, and power electronics module lifetime reduction

Summary of 2014 Outcomes

- Improved high temperature performance
  - New high temperature novel dielectrics with high permittivity and low loss were produced
- Reduced capacitor volume
  - New dielectrics exhibit high permittivity and high energy density
- High reliability focus
  - Evaluated long term resistivity changes
  - High resistivity, large activation energy and microstructure tied to defect chemistry
- Cost
  - Reduced cost by elimination of Sc_2O_3 batch ingredients
  - Technology transfer for scalable manufacturing

Impact on system

- High power
- High efficiency
- Reduced thermal management

- High power density
- Reduced system volume

- Reduced losses
- Increased system lifetime, reliability
- Predictable MTTF

- Working with dielectric supplier and capacitor manufacturer

IP and Publications

FY14 Technical Advances

1. G.L. Brennecka, H.J. Brown-Shaklee, D.P. Cann, N. Raengthon, and N. Kumar, *Thermally Stable High Performance Dielectrics*. (May 2014)

2. H.J. Brown-Shaklee, *Multilayer electrostatic capacitor with internally embedded Peltier cooled electrode elements*. (August 2014)

FY14 Publications

1. N. Triamnak, G.L. Brennecka, H.J Brown-Shaklee, M.A. Rodriguez, and D.P Cann, "Phase formation of $BaTiO_3$- $Bi(Zn_{0.5}Ti_{0.5})O_3$ perovskite ceramics," *Journ. Cer. Soc. Jap.* 122 [4] 260-266 (2014).
2. H.J. Brown-Shaklee, J.J Borchardt, N. Raengthon, D.P. Cann, and G.L. Brennecka "Pulse discharge behavior of relaxor dielectric multilayer ceramic capacitors," *Proc. 16th US-Japan Sem. on Dielect. and Piezo. Mater.,* pp. 118-20 2013.
3. D.P. Cann, N. Raengthon, N Triamnak, H.J. Brown-Shaklee, I.M Reaney, and G.L Brennecka, "$BaTiO_3$-$Bi(Zn_{0.5}Ti_{0.5})O_3$ relaxors for advanced capacitor applications," *Proc. 16th US-Japan Sem. on Dielect. and Piezo. Mater.*, pp. 58-63 2013.
4. H.J. Brown-Shaklee, M.A. Blea-Kirby, A. Casias, A. Wagner, and G.L. Brennecka, "Co-fire processing of $(Bi_{0.2}Ba_{0.8})(Zn_{0.2}Ti_{0.9})O_3$ relaxor multilayer ceramic capacitors," *In preparation.*

Conference Presentations

FY14 Technical Presentations

1. D.P. Cann, N. Raengthon, N Triamnak, H.J. Brown-Shaklee, I.M Reaney, and G.L Brennecka, "$BaTiO_3$-$Bi(Zn_{0.5}Ti_{0.5})O_3$ Relaxors for Advanced Capacitor Applications," ***Plenary*** *at the 16th US-Japan Sem. on Dielect. and Piezo. Mater.*, Rayleigh, NC (Nov. 2013).

2. G.L. Brennecka , H.J. Brown-Shaklee, J.J Borchardt, N. Raengthon, and D.P. Cann, "Direct time domain measurement of relaxor response," ***Invited Talk***, *presented at the 16th US-Japan Sem. on Dielect. and Piezo. Mater.,* Rayleigh, NC (Nov. 2013).

3. G.L. Brennecka, H.J. Brown-Shaklee, N. Raengthon, N Triamnak, D.P. Cann and S. Atcitty, "Capacitor development for reliable high temperature operation in inverter applications," ***Invited Talk***, presented at the TMS Spring Meeting, San Diego, CA (2014).

4. G.L. Brennecka, H.J. Brown-Shaklee, M.A. Blea, N. Reangthon, and D.P. Cann, "High Reliability Ceramic Capacitors Based on Temperature and Voltage-Stable Relaxor Dielectrics for High Operating Temperature Inverter Applications," *Presented at Materials Challenges and Applications for Renewable Energy (MCARE)*, Clearwater Beach, FL (Feb. 2014).

Next Steps: FY15 Milestones

- Reduce cost of dielectric by substitution of scandium oxides
- Demonstrate industrial manufacturability with commercial partners from powder synthesis to MLCC production
  - Establish in kind CRADA with at least one commercial partner
- Benchmark existing commercial NP0 dielectrics against newly developed industrially produced MLCCs
- Evaluate thermal behavior of dielectric packages during switching operation

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